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AN OVERVIEW OF THE SAFETY CASE FOR SMALL MODULAR REACTORS

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ABSTRACT

Several small modular reactor (SMR) designs emerged in the late 1970s and early 1980s in response to lessons learned from the many technical and operational challenges of the large Generation II light-water reactors. After the accident at the Three Mile Island plant in 1979, an ensuing reactor redesign effort spawned the term "inherently safe" designs, which later evolved into "passively safe" terminology. Several new designs were engineered to be deliberately small in order to fully exploit the benefits of passive safety. Today, new SMR designs are emerging with a similar philosophy of offering highly robust and resilient designs with increased safety margins. Additionally, because these contemporary designs are being developed subsequent to the September 11, 2001, terrorist attack, they incorporate a number of intrinsic design features to further strengthen their safety and security. Several SMR designs are being developed in the United States spanning the full spectrum of reactor technologies, including water-, gas-, and liquid-metal-cooled ones. Despite a number of design differences, most of these designs share a common set of design principles to enhance plant safety and robustness, such as eliminating plant design vulnerabilities where possible, reducing accident probabilities, and mitigating accident consequences. An important consequence of the added resilience provided by these design approaches is that the individual reactor units and the entire plant should be able to survive a broader range of extreme conditions. This will enable them to not only ensure the safety of the general public but also help protect the investment of the owner and continued availability of the power-generating asset. Examples of typical SMR design features and their implications for improved plant safety are given for specific SMR designs being developed in the United States.

PREFACE

On March 11, 2011, the Fukushima Daiichi nuclear power plant in Japan was severely damaged by the combined impact of an extreme earthquake and resulting tsunami. The situation continues to evolve and the full consequences of the accident are not yet known. The combined earthquake/tsunami disaster and its impact on the affected nuclear reactor units will clearly have many implications, both negative and positive, on the global fleet of existing reactors and plans for new plants and designs. This paper was prepared in direct response to the Fukushima event and is intended to provide a broad cross-design perspective on the anticipated safety attributes of small modular reactors (SMRs). It also provides an initial assessment of high-level implications on a new SMR program proposed by the US Department of Energy (DOE).

BACKGROUND

Several SMR designs emerged in the late 1970s and early 1980s in response to lessons learned from the many technical and operational challenges of the large Generation II light-water reactors (LWRs), including lessons from the accident at Three Mile Island in 1979. These designs sought to add qualities of robustness and resilience to nuclear plants and spawned the term "inherently safe" designs, which later evolved into

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"passively safe" terminology. A major study led by Alvin Weinberg[1] in 1983 observed that successful expansion of nuclear energy would require new plants to be much less sensitive to minor perturbations, respond more slowly to system upsets, and be able to recover from those upsets without immediate operator action. This added level of plant resilience is needed to not only further ensure public safety but also protect owner investment and improve public acceptance. The conclusion was that some of the specific new designs that had emerged at that time, such as the Process Inherent Ultimate Safety (PIUS) design and the modular high-temperature gas-cooled reactor (MHTGR) design, appeared to offer significantly improved plant resilience. It was also concluded that smaller-sized reactors seemed to provide the best opportunity for achieving the desired level of resilience but also created concern regarding their economic viability.

The large Generation III and III+ reactor designs that are now being sold and constructed around the world also originated after the Three Mile Island accident and explicitly emphasize plant safety and robustness. Many of them include passive safety features to some extent, although some designs rely on additional system redundancies to achieve the desired safety goals. All of the systems provide additional layers of protection from the kind of situation that occurred at the Fukushima Daiichi plant and allow the operators additional response time. Contemporary SMR designs build on this principle and are able to make even greater use of passive safety features due to their smaller size and design simplifications.[2] As discussed in the following section, the result is an emerging collection of highly robust and resilient designs with increased safety margins. These designs build on the strong safety philosophy of the original SMR designs of the 1980s and the large Generation III plants with the added benefit of three decades of design and operational experience of large plants. Additionally, because the designs are being developed subsequent to the September 11, 2001, terrorist attack and the recent natural disaster at the Fukushima Daiichi site, they incorporate a number of intrinsic design features to further strengthen their safety and security.

THE SMR SAFETY CASE

Several SMR designs are being developed in the United States spanning the full spectrum of reactor technologies. Some are based on mature water-cooled reactor technology and have the potential for near-term deployment. The most mature designs include the 45 MWe "NuScale" design[3] developed by NuScale Power, the 125 MWe "mPower" design[4] developed by Babcock and Wilcox, and the 200 MWe "W-SMR" design[5] developed by Westinghouse Electric. Very recently, the 140 MWe "HI-SMUR" design[6] was announced by Holtec International. Several non-LWR SMR designs are also being developed by industry and especially within the national laboratory complex. These designs also feature enhanced safety margins and resilience; however, the focus of this paper is on the LWR-based SMR designs due to their close similarities.

Despite a number of design differences, these SMR designs share a common set of design principles to enhance plant safety and robustness. Some of the intrinsic design features, which appear in some or all of the four designs listed above and help achieve a higher level of plant resilience, are described below.

Incorporation of primary system components into a single vessel. The NuScale, mPower, and W-SMR designs use an integral pressurized-water reactor (iPWR) design in which all or most of the primary system components are contained within a single vessel. This is a critical design simplification feature that is central to both the improved safety case and the potential for economic competitiveness. It is also the primary feature that keeps the reactor output relatively small due to the limited volume within the vessel. The integral design eliminates the high-consequence accident scenario of a large pipe-break loss-of-cooling accident and greatly reduces the number and size of penetrations through the reactor pressure vessel. In an iPWR the maximum size pipe penetrating the reactor vessel is 5–7 cm in diameter, which is needed for the feed-water inlet and steam outlet of the internal steam generator. This is in contrast to the 80–90 cm diameter pipes in a large loop-type pressurized-water reactor (PWR) that connect the reactor vessel to the external steam generator vessels. A comparison of the two systems is given in Fig. 1.

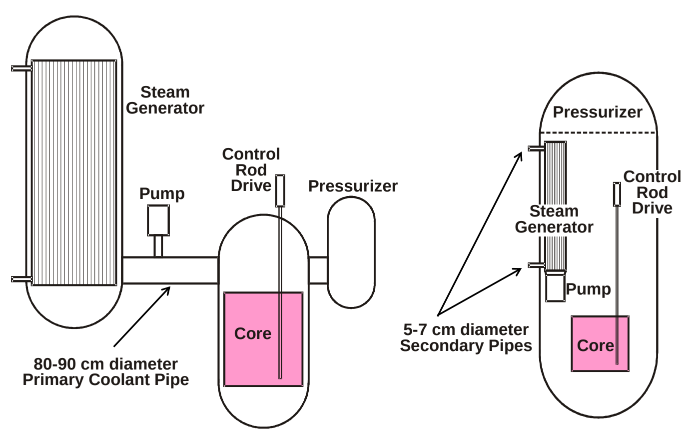

Fig. 1 Comparison of loop-type PWR (left) and iPWR (right) showing elimination of large primary coolant pipes

Increased relative coolant inventory in the primary reactor vessel. Placing all of the primary components within the reactor vessel requires that the vessel be relatively large compared to one used in a loop-type configuration. Also, the integral configuration results in the entire inventory of primary coolant being contained within the reactor vessel. The combination of a larger vessel and consolidation of primary coolant yields a larger inventory of water per unit of power than in the loop-type plant, which increases the relative thermal inertia within the reactor vessel due to the favorable heat capacity of water. As an example, the NuScale design has a fourfold greater volume of cooling water in the reactor vessel per unit of power than does a traditional four-loop PWR design. The result is a corresponding reduction in the rate at which the system temperature increases during a loss of forced flow transient, which in turn provides the operators with more time to respond to an upset condition.

Increased relative pressurizer volume. The purpose of the pressurizer is to maintain a constant pressure in the primary coolant circuit and buffer against pressure transients. In the International Reactor Inherently Safe (IRIS) SMR design[7] (an iPWR previously developed by a Westinghouse-led consortium), the pressurizer volume was roughly five times larger per unit of power than for a conventional PWR. This design feature dramatically reduces the impact of a reactor pressure transient and provides the operator additional response time.

Smaller radionuclide inventory. The radionuclide inventory in a reactor core, which represents the dominant radiation hazard in a nuclear plant, is roughly proportional to power level. Therefore, a 150 MWe reactor will have one-tenth the amount of radionuclides in the fuel elements compared to a 1500 MWe reactor. The amount of radiation hazard assumed to be released in an accident, referred to as the source term, is a combination of the radionuclide inventory and the potential release paths. In addition to the intrinsically smaller radionuclide inventory of an SMR, some SMR designs such as NuScale add additional barriers to fission-product release to achieve a dramatically smaller accident source term. Multimodule plants (i.e., plants that are comprised of several SMR units) will have a proportionately larger radionuclide inventory; however, the reference plant size for NuScale (12 modules) and mPower (4 modules) is nominally 500 MWe—still only one-third the size of a typical large plant.

Vessel and component layouts that facilitate natural convection cooling of the core and vessel. Accommodating all of the primary system components in a single vessel, while also constraining the vessel diameter to truck or rail transport limits, results in the iPWR reactor vessel being proportionally taller than a loop-type PWR one. For example, the vessel height-to-diameter ratio for a typical large PWR is roughly 2.5 and for a large boiling water reactor (BWR) about 2.0. In contrast, the W-SMR and mPower designs have an aspect ratio exceeding 6.0. This increase in the aspect ratio greatly facilitates the formation of gravity-driven natural convection circulation of the coolant, which enhances heat removal from the core and allows the plant to cool down safely in the event of loss of off-site power without a requirement for emergency power (e.g., diesels or batteries) to drive circulation pumps. In some SMR designs such as NuScale and HI-SMUR, the natural circulation driving force is designed to be sufficiently strong to be used as a core cooling mechanism for full power operation, thus eliminating the need for pumps entirely. Figure 2 compares a typical large PWR reactor vessel to the mPower iPWR vessel.

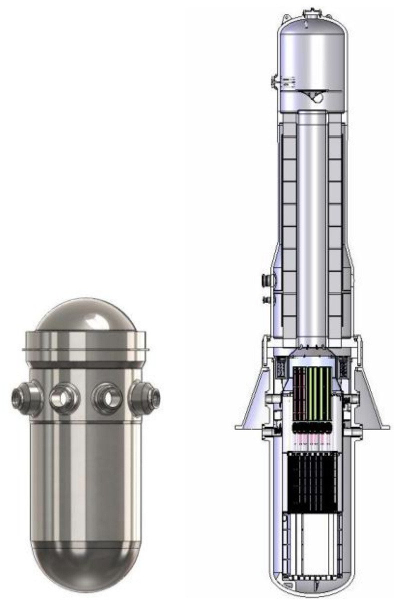

Fig. 2 Approximately scaled comparison of typical large PWR reactor vessel (left) with the mPower iPWR reactor vessel (right) showing the increased aspect ratio of the iPWR vessel

More effective decay heat removal. Most SMRs have reactor vessel diameters of 2.5–3.5 m compared to 4–6 m for large PWRs and 6–7 m for large BWRs. The dimensionally smaller reactor core and reactor vessel of an SMR yields a shorter distance from the core centerline to the reactor vessel, thus allowing better radial coupling of the decay heat from the reactor core to the vessel where it can be removed by external cooling of the vessel surface. Also, the relative surface area of the iPWR vessel per unit power is increased due to both the smaller diameter vessel and the larger vessel aspect ratio. The combined result of these factors is that the effectiveness of heat removal from the exterior of the vessel is estimated to be two to four times larger than heat removal from the vessel surface of a traditional large plant.

Smaller decay heat. Reactor decay heat must be removed from the reactor core for an extended period of time after the reactor is shut down to avoid fuel damage. The decay heat power is roughly proportional to full power capacity; therefore, a 150 MWe reactor will have one-tenth the amount of the decay heat power of a 1500 MWe reactor. It is important to note that even though the SMR will have smaller decay heat power than a large plant, it can still be a significant amount of power, and fuel damage will occur unless the decay heat is adequately dissipated through one or more removal paths. The smaller decay heat power in combination with the improved axial and radial heat removal paths discussed in the previous paragraphs provide the potential for significantly reduced risk of fuel damage and consequential fission product release.

Below-grade construction of the reactor vessel and spent fuel storage pool. The smaller plant footprint of an SMR makes it more economically viable to construct the primary reactor system fully below ground level, which significantly hardens it against external impacts such as aircraft or natural disasters. As an example, the new W-SMR design has a containment vessel volume that is more than 23 times smaller than the Westinghouse AP-1000 containment. In addition to hardening the primary system to external impacts, below-grade construction helps reduce the number of paths for fission-product release in the event of an accident.

Enhanced resistance to seismic events. Below-grade construction of the reactor and containment vessels also provides the potential for additional seismic resistance. SMR designers like those working on the NuScale design are incorporating other advanced design features such as trunion supports on the reactor vessel and immersion of the containment vessel in a large water pool to further protect the plant against seismic events. In addition to enhancing the seismic robustness of the plant, these design features allow greater flexibility in siting of the SMR, which enables a greater level of plant design standardization.

The cumulative impact of the added resilience provided by these collective design choices is that the individual reactor units and the entire plant should be able to survive a broader range of extreme conditions. This will enable them to not only ensure the safety of the general public but also help protect the investment of the owner and continued availability of the power-generating asset. Additionally, because the designs are still being developed, they will be able to incorporate changes based on the important conclusions from the numerous impact studies that will be conducted by the US Nuclear Regulatory Commission, US industry, international organizations, and other stakeholders regarding the Japan tragedy.

MOVING SMRS FORWARD

As the preceding section demonstrates, SMRs offer the potential for enhanced safety and plant resilience by virtue of innovative design choices. The LWR-based SMR designs mentioned above have the potential to progress to market quickly and provide the opportunity for the United States to move forward with demonstrating the safety benefit of SMRs. Research and development (R&D) of new technologies can further enhance the safety and resilience of the next-generation SMRs, but these SMRs will take longer to develop and qualify for commercial application.

A new program being proposed by DOE seeks to facilitate the further development and commercial deployment of SMRs domestically. The proposed DOE SMR program has two distinctive components: (1) support the design finalization and licensing of first-mover SMR designs and (2) conduct research, development, and demonstration activities supporting the deployment of advanced SMR designs. The first component will establish competitively awarded, public-private partnerships to fully license the first-to-market SMRs as a means of demonstrating the licensability of SMRs and will be the first step in demonstrating their affordability and cost competitiveness. The R&D component is intended to accelerate the development of more robust fuels, materials, manufacturing methods, instrumentation, and designs needed to enable a new generation of SMRs with further improvements in the level of safety, security, resilience, and affordability. Modern experimental capabilities—especially the enormous simulation capabilities afforded by massively parallel supercomputers—will expedite the development of the new technologies toward the goal of the "inherently safe" nuclear plant envisioned by the nuclear pioneers such as Weinberg.

The DOE program will focus on developing new nuclear technologies and systems that are as safe and robust as reasonably achievable. As with other DOE advanced nuclear technology programs, the SMR program will be actively seeking to incorporate the experience of the Japanese disaster into future planning. The program will closely coordinate with the US Nuclear Regulatory Commission as it develops its short- and long-term responses to the Japan experience in terms of the licensing and regulation of US nuclear plants. Although lessons learned from the Fukushima Daiichi plant will continue to evolve, some immediate implications on the planned DOE SMR program include those below:

- The review and selection of proposed SMR designs for the planned public-private partnerships to demonstrate licensing of new SMR designs will emphasize designs that offer the greatest robustness and resilience to internal and external upsets.
- The R&D portion of the planned program will place the highest priority on developing technologies, capabilities, and designs that further quantify, enhance, and demonstrate plant safety, robustness, and resilience, such as
  - exploration of novel reactor concepts that specifically exploit the features of SMRs to

achieve unprecedented levels of passive/inherent safety;
- reliability of passive safety systems that don't require backup electrical generators;
- seismic isolation for deeply embedded reactor systems and coupling to balance of plant systems;
- common cause upset modes and mitigating approaches in multimodule plants; and
- fuels, materials, and sensors that are highly resistant to extreme conditions.

Finally, the R&D community, industry, and the regulators must work together to ensure that the technology and engineering differences incorporated into the designs do not inadvertently introduce new plant vulnerabilities.

CONCLUSIONS

The global nuclear energy industry, and especially the US nuclear industry, has demonstrated a high level of safety achievement. Still, the natural disaster in Japan has highlighted the reality that extreme events can occur. The nuclear industry and research communities must vigilantly seek to further improve the safety and resilience of nuclear power plants if nuclear energy is to remain a viable element in our clean energy portfolio. The new generation of large plants offer significant improvements and small modular reactors have the potential to achieve an unparalleled level of safety and plant robustness by virtue of their intrinsic features. Several SMR vendors are actively developing new designs that build on the successes and learn from the failures of existing plants. The new designs reflect a common set of design principles such as eliminating plant design vulnerabilities where possible, reducing accident probabilities, and mitigating accident consequences. An important consequence of the enhanced safety and added resilience provided by the many design features reviewed in this paper is that the individual reactor units and the entire SMR plant should be able to survive a significantly broader range of extreme conditions. This will enable them to not only ensure the safety of the general public but also help protect the investment of the owner and continued availability of the power-generating asset. What remains is for the nuclear industry and the government to work together to make SMRs a demonstrated reality.

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